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NOAA Technical Report NESDIS 43

Adjustment of Microwave Spectral Radiances of the Earth to a Fixed Angle of Propagation

Washington, D.C.
December 1988

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service

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Adjustment of Microwave Spectral Radiances of the Earth to a Fixed Angle of Propagation

D. Q. Wark

National Environmental Satellite, Data, and Information Service
Office of Research and Applications
Washington, D.C.
December 1988

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ADJUSTMENT OF MICROWAVE SPECTRAL RADIANCES OF THE EARTH TO A FIXED ANDGLE OF PROPAGATION

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ABSTRACT. Data from the Special Sensor, Meteorological/Temerature (SSM/T) on the Defense Meteorological Satellite Program satellites F7, F8, and F9 have been used to calculate limb-adjustment coefficients to transform all data to the values they would have in a vertical view. It is demonstrated that radiance temperatures averaged in one-degree latitudinal belts at different angles of view can be used successfully to compute the coefficients, provided the sample is large. The channels used in each adjustment are limited to those which have meaningful physical relations. It is shown that the latitudinal means used in a least-squares solution for the coefficients represent typical individual sets of measurements. It is further shown that increased noise and errors due to errors of estimate of the coefficients are of little or no concern. A seasonal update of the coefficients for two satellites is performed with beneficial results.

I. Introduction

Several artificial satellites have carried microwave radiometers which scan in several angles perpedicular to the motions of the satellites. In particular, the Microwave Sounding Unit (MSU) on the TIROS-N and the NOAA-6 through NOAA-10 satellites and the Special Sensor, Meteorological, Temperature (SSM/T) on the Defense Meteorological Satellite Program (DMSP) spacecraft F7, F8, and F9 have been devoted to indirect temperature soundings of the atmosphere for meteorological applications.

One undesirable feature of the cross-track scanning is that radiation in individual beam positions arises from somewhat different levels in the atmosphere. This results in different radiance values in different angles of view from a horizontally homogeneous atmosphere having a homogeneous surface as a background.

The equation of radiative transfer states that the radiance of the source being measured is, for a non-scattering atmosphere in local thermodynamic equilibrium,

$$R(\nu,z) = R_s(\nu,z)\tau(\nu,z,p_s) + \int_{p_s}^{0} B[\nu,T(p)]d\tau(\nu,z,p), \qquad (1)$$

where R is spectral radiance at the frequency ν and the local zenith angle z; τ is the spectral transmittance of the atmosphere at frequency ν in the direction z from pressure level p to p = 0; and B is the Planck radiance at frequency ν and atmospheric temperature T, which varies with pressure p.

The subscript s indicates the value at the surface; for atmospheric "windows" the surface radiance is composed of both emitted and reflected components in the microwave, whereas it is very nearly the Planck radiance at infrared wavelengths (emissivity $\varepsilon \approx 1.0$).

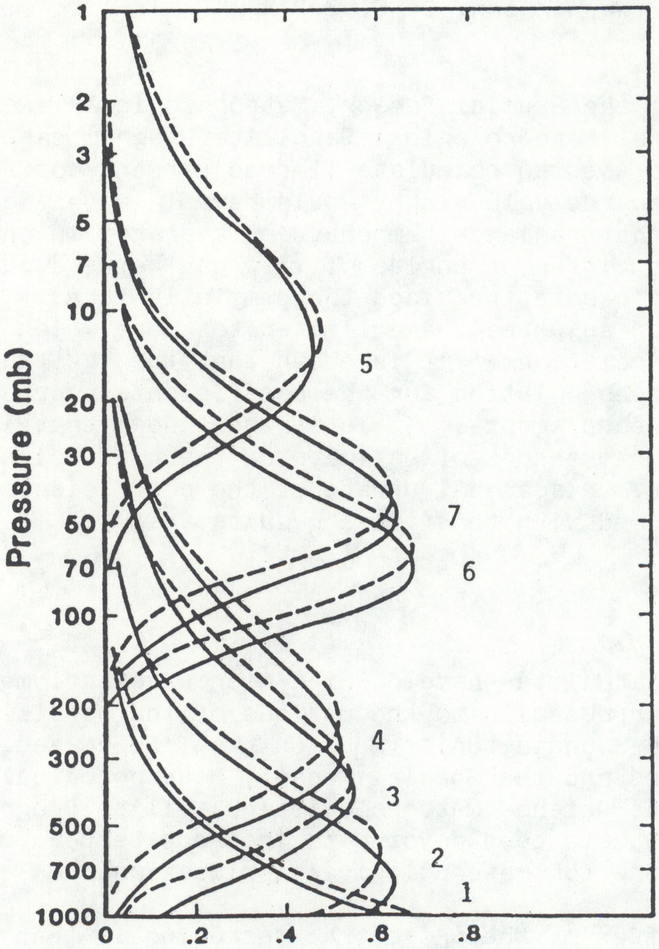

Figure 1. Calculated transmittance weighting functions for the seven channels of the SSM/T (Grody, et al., 1987). Dashed lines apply to the extreme scan angles; solid lines apply to the nadir direction.

Figure 1 illustrates the weighting functions, $d\tau(\nu,z,p)/d\log(p)$, at two angles of view for the seven channels of the SSM/T; the term "weighting function" derives from the definition of a weighted mean, so that atmospheric radiances are mean weighted Planck radiances. At the largest angle of scan (36 degrees from the nadir at the satellite, or 41.65 degrees zenith angle of the satellite as viewed from the ground), it is seen that the weighting functions have moved up in the atmosphere with respect to the nadir view (zero nadir and zenith angles). Thus, in those parts of the atmosphere where temperature decreases with pressure (the troposphere, in general), the contributions to a radiance will be less at the large angle of view, while in those parts of the atmosphere in which temperature increases with decreasing pressure (as in the stratosphere) the contributions to a radiance will be greater at the large angle of view. Those channels having their weighting functions predominantly in one regime or the other will show decreasing or increasing radiances with increasing scan angle. These effects are commonly known as "limb-darkening" or "limb-brightening", terms derived from the astronomical lexicon which are attributable to observations of the sun in visible light.

To confirm this phenomenon, radiance temperatures (temperatures of a Planck blackbody having the same spectral radiances) have been selected from SSM/T data in areas having no clouds, and are presented in Table 1. The first case is over the tropical Atlantic Ocean, and the second is over tropical Africa about 100 minutes earlier. It will be seen that all channels have different readings for the two angles in each case, but those channels insensitive to surface contributions (Channels 3-7) have almost identical values for the same angle at the two locations. This suggests that the atmosphere has nearly the same temperature profile over the two regions, and that the differences in the radiances arise from angles of view and the nature of the surface. Channel 5 is unreliable because the space reading during calibrations was off scale; however, the errors are not large, and the relative values are probably satisfactory.

Table 1. SSM/T radiance temperatures in degrees Kelvin in two locations at two angles of view, September 22, 1986 from the F7 spacecraft. Observations were at about 10:30 a.m. local time.

Channel	Case 1, ocean		Case 2, land	
No.	z = 0	z = 41.65	z = 0	z = 41.65
1	224.12	236.44	286.27	283.16
2	259.50	257.19	268.80	261.98
3	240.77	233.34	241.77	233.23
4	226.70	220.27	227.02	220.69
5	231.98	233.06	231.02	232.20
6	210.17	211.19	209.62	211.70
7	214.92	216.39	214,80	216.55
Lat./Lon.	21S/8E	21S/2E	19S/33E	21S/27E

The differences between ocean and land for Channels 1 and 2 result from the much lower emissivity of sea water (less than 50 percent) with respect to that for dry land (greater than 90 percent). Because neither of these surfaces is a black emitter ($\varepsilon = 1.0$), the boundary term in Eq. (1) is rather complicated. Qualitatively, the radiance of a water surface corresponds to a radiance temperature of about 130-150K, to which there is a reflected contribution from the atmosphere, which in turn is smaller for the more transparent frequencies. Eq. (1) then states that the radiance is the sum of the surface contributions attenuated by the atmosphere (transmittance at the surface) and supplemented by emission from the atmosphere. One result of the differing surface emissivities is that an observation in the most transparent channel, Channel 1, displays limb-brightening over the ocean and limb-darkening over the land.

In the presence of clouds, particularly those having raindrops, the second term on the RHS of Eq. (1) does not hold in that form because of the scattering by the particles. A fuller discussion of this effect should be sought elsewhere. However, the effect of cloud and rain drops is to increase radiances for Channel 1 at all angles of view over water, and to decrease radiances over the land; for other channels affected by cloud and rain drops (chiefly Channels 2 and 3) the effect is to decrease radiances everywhere.

In the application of the measurements, one must account for both the boundary term and the angular variation of atmospheric contributions. A commonly-used simplification of the reduction of the measurements to temperature profiles is to "adjust" each set of measurements to a common angle of view (preferably the nadir direction). One way of accomplishing this is to compute from theory the radiances that would be found at the various angles for a range of atmospheric profiles, surface conditions, and cloud-particles (particularly rain). These data are then fit by regression to a linear combination of the channels for adjusting each channel to the value it would have in the nadir direction. This is the method used for the MSU.

However, nature seldom agrees with theory because theory is usually inexact. Errors arise from each of the contributions to the radiances: the nature of the surface, the atmospheric transmittances, and the cloud contributions. Such is the case for the MSU, with resulting systematic errors in the angle-adjusting process.

There is only one source of correct data, the measurements themselves. And because there is no measurement of exactly the same conditions at each viewing angle, one must appeal to statistical methods.

II. The data samples

Most of the SSM/T data and results presented here are taken from the F9 spacecraft, which was the third to carry that instrument. There have been two additional SSM/T instruments carried aboard the F7 and F8 spacecraft, and the limb-adjustment coefficients for them are given in the Appendix. Data samples for all three were the same size; data from the F7 were obtained at the northern autumnal equinox, while those from the F8 and F9 were obtained during the northern Spring.

Measurements by the SSM/T have been accumulated during periods of six to seven days covering September 22-29, 1986, March 31-April 7, 1988, and April 18-24, 1988 for the F7, F8, and F9 spacecraft, respectively. Missing orbits have reduced each sample to about six days, encompassing 114,960 measurements of each of the seven channels, giving 16,422 sets of data for each of the seven beam positions. The task now is to reduce this sample to the data which will provide essential information, and which will not degrade the final results.

A. Bad or missing data

Some of the data are already flagged and therefore missing; these amount to 200-400 sets for each satellite. It is also necessary to detect and delete badly calibrated data or data which are obviously incorrect. This was done by visual inspection, but objective methods are required in an operational system. The number of data falling into these two categories amounted to no more than 100 for each satellite. It is essential, though, that these data are eliminated.

B. High latitude data

The orbital inclination of the DMSP satellites is slightly more than 81 degrees. For a left-to-right scan, the left beam position never passes north of about 76N, and the right beam position never passes south of about 76S. For the vertical view, which is used as the reference, the maximum latiudes are 82N and 82S. The data set was therefore limited to the range 82N-82S, with no data in some left beam position at latitudes 76-82N and in some right beam position at latitudes 76-82S. In the process about 3,000 non-coastal observations are eliminated.

C. High terrain

Channel 3 is virtually opaque to sea-level surfaces, but over high terrain, especially above 1500 meters, the boundary is lifted up substantially in the weighting function (see Figure 1). For Channels 1, 2 and 3 the relative contributions by the surface and atmosphere are significantly altered over high elevations, and it was at first thought the inclusion of these data would do harm to the statistical processes. However, when data over Greenland, the Tibetan Plateau, the Iran Plateau, the South American Altoplano, and the Antarctic continent were included, the range of surface and atmospheric conditions was extended and no apparent degradation in the final results was observed.

D. Coastline observations contain both high and low emissivity surfaces, with each observation having a different percentage of each surface type. This will lead, in the processes given later, to latitudinal means for the channels sensitive to the surface (Channels 1 and 2) which cannot, given the size of the sample, be consistent between beam positions. This was confirmed in a test not presented here.

With the deletion of the data in sections II.A., II.B. and II.D. above, each sample was reduced to about 94,000 sets of measurements (82 percent of the total).

III. Statistical behavior of the sample

Figure 2. shows histograms for two of the F7 and F9 SSM/T beam positions for each of the seven channels. The extreme left position (number 1) and the nadir position (number 4) were chosen to illustrate the extent of the limb effects and the amount of adjustment which is required under these conditions. The following are the characteristics which are readily apparent:

In Channels 2-7 there are maxima, often very sharp, which represent observations in the tropics. As a whole, the tropics have little variation, but they constitute a sizable fraction of the data. At higher latitudes the atmospheric temperature is quite variable and non-tropical in nature. These are the remaining data in the histograms.

There are a number of other characteristics in the histograms, which are readily apparent:

A. In Channel 1 there are two modes, representing, roughly, ocean (left) and land (right), although the lowest values are over the land of the Antarctic continent. There is considerable limb brightening over the oceans, and modest limb darkening over the highest values.

B. In Channel 2 there is limb darkening, but it is more pronounced at the higher values than at the lower values. The small maximum at the upper end for the nadir view represents the hottest desert areas, a feature which is lost in the left-hand view because of the greater opacity of the atmosphere.

C. In Channels 3 and 4 there is very substantial limb darkening at all values. Channel 4 is of particular interest because the skewness is reversed in the two beam positions. This is caused by the transition from limb darkening to limb brightening which occurs when passing from the tropsphere to the stratosphere; Channel 4 is near this transition zone, and the "lifting" of the weighting function (see Figure 1.) is responsible for this feature.

D. Channels 5, 6, and 7 show limb brightening, although it is not present at the highest values for Channels 6 and 7. These channels reveal somewhat different characteristics in the two figures which are the results of radically different stratospheric conditions at the times of the observations. The generally lower values for the F9 satelite may be ascribed to a seasonally colder stratosphere.

Perhaps the most salient feature of these histograms is the wild departures of the distributions from the Gaussian. Each channel and each beam position has its unique distribution, which can be described only in many high order moments. The effect is that the usual statistical quantities such as means, variances and covariances do not have simple interpretations. This precludes some statistical approaches to the solution of limb adjustment, but does leave an obvious alternative.

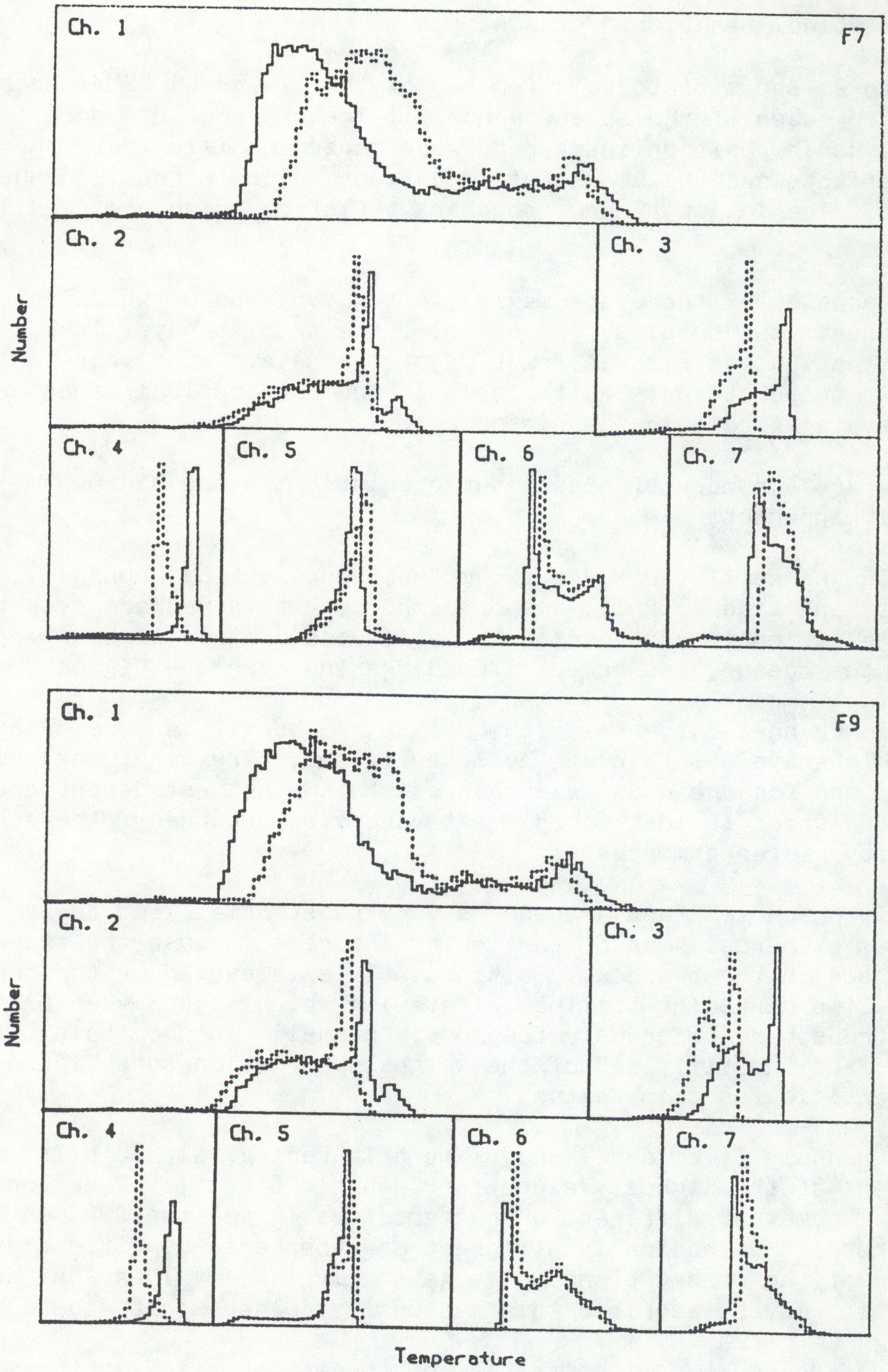

Figure 2. Histograms of SSM/T data for the F7 (upper) and F9 (lower) satellites in one-degree increments. Beam position 1 is shown as dashed lines and beam position 4 as solid lines. The full-scale temperature range of the abscissa is 168 degress K. Each latitude receives equal weight; the vertical scale is normalized to the greatest value in both beam positions. Data 76-90N and 76-90S and data deleted in section VI are omitted.

IV. Principles of a limb-adjustment algorithm

The goal of this study is to formulate the angle adjustments as a set of linear coefficients applied to measurements in several interdependent channels. This takes the linear form

$$T_{i0} = a_{ik0} + \sum_{j}(a_{ijk}T_{jk}), \tag{2}$$

where T_{i0} is the adjusted radiance temperature of channel i to the zero (nadir) direction; a_{ik0} is a constant associated with Channel i and beam position k; a_{ijk} is a coefficient associated with Channel i, beam position k, and associated channel j; and T_{jk} is radiance temperature at beam position k for associated channel j. An associated channel is defined as one which is used in adjusting a particular channel, and may, in principle, include all channels; this matter is discussed later.

If one has radiance values for a variety of atmospheric and surface conditions at each viewing angle, Eq. (2) may be solved for the coefficients by some regression procedure (step-wise regression, least squares, etc.). However, measurements are never located at all angles at the same location for the same conditions. Indeed, the size of the viewed area increases with nadir angle, which militates against identity of scene conditions. Even the complementary views from right and left are oriented differently and may have different antenna patterns. Add to this the complications brought on by constantly-changing cloud and precipitation characteristics, surface heating and cooling, and the effects of wind on ocean emissivity, all of which influence the lower channels. Thus, a particular set of conditions cannot be observed at each viewing angle.

Numerous statistical approaches have been made to the problem. Some of these require that the distributions of observations must be Gaussian. However, these procedures fail because the data are distributed in very non-Gaussian fashion, as shown earlier.

The effect of the poor distributions of data is similar to that of noise. The coefficients compensate too little, and the adjustments tend toward the mean. This tendency is suppressed in a simple linear regression of known variations of radiance temperatures (or radiances) with viewing angle.

An effective means of obtaining a consistent set of radiances is to find the mean values in one-degree latitude belts over the range of latitudes which are allowed (82S to 82N). This requires a large set of data, so that each beam position at each latitude will, on the average, sample the same sets of radiances. This assumes that, within the time span of the sample (five to seven days), the surface and and the atmosphere will not undergo drastic changes. It also assumes that the variances about the means will not be so large that the means themselves may not be representative of the sub-sample. Under ideal conditions, there would be zonal flow at all levels of the atmosphere, so that latitudinal variances would be minimized.

To accommodate to the special needs of Channels 1 and 2, the data are separated by surface type (land, ocean and ice). The data over ice tend to be erratic because of the varying mean emissivity of the surface with the fields of view; however, this factor did not render the data useless, as was the case for coastlines. The division into separate means by surface type extends the ranges of the latitudinal means, which becomes vital when solving for the coefficients by least squares, where the end points in a distribution are more important than data near the mean.

V. Associated channels

It is readily apparent that regression can lead to errors, particularly when applied to data which are not part of the sample. For example, there is a sizable negative correlation between surface temperature and the temperature in the stratosphere. It would be imprudent, however, to apply this correlation to estimate a temperature at some level in the stratosphere. This is also true for the SSM/T channels, and the effect is worsened by the effects of surface emissivity. There is no overlap in the weighting functions for Channels 1 and 5, so there is no justification making a limb adjustment of the latter based on the former.

On the other hand, correlations between channels can be useful in choosing those channels which are employed to adjust a single channel for limb effects. To illustrate this, correlations have been found for the SSM/T beam positions 1 and 4 (extreme left and nadir, respectively), based on covariances derived from deviations from latitudinal means, and are presented in Table 2. It will be noted that Channels 5, 6 and 7 are negatively correlated with Channels 1, 2 and 3; on the other hand, Channel 5 is positively correlated with Channel 4. These statistical correlations relate to the behavior of the atmospheric temperature, but do not necessarily indicate the relations of the channels in the radiative transfer process. This table may be examined to gain further insight.

Table 2. Correlations of the SSM/T channels for beam position 1 (upper half) and beam position 4 (lower half).

B.P.	Ch.\Ch.	2	3	4	5	6	7
1	1	.719	.405	.007	-.074	-.121	-.086
1	2	1.000	.645	-.047	-.099	-.298	-.230
1	3		1.000	.506	-.041	-.098	-.078
1	4			1.000	.085	.518	.402
1	5				1.000	.322	.543
1	6					1.000	.908
4	1	.747	.480	.177	-.023	-.-51	-.018
4	2	1.000	.818	.255	-.067	-.206	-.155
4	3		1.000	.548	-.060	-.211	-.176
4	4			1.000	.074	.372	.291
4	5				1.000	.336	.532
4	6					1.000	.920

It is not proper to rely upon global or even regional correlations as a basis for predicting some quantity from a combination of channel measurements. Although these correlations hold for the average, they can be devastatingly destructive for individual cases. Therefore, certain channels should be forbidden in deriving limb adjustments. Channels totally opaque to the surface (Channels 4-7) should not use those channels with significant surface contributions (Channels 1 and 2); Channel 3 is a special case over high elevations. It is intuitively obvious that the channels immediately above and below a channel can contribute very significantly in making a limb adjustment. This is the basis for a proposed selection of associated channels. However, if step-wise regression is used instead of multiple linear regression with pre-selected channels, one should not permit certain channels into the process. Table 3. summarizes the conclusions drawn on associated channels in this study.

Table 3. Associated channels for the SSM/T.

Channel	Adopted associated channels	Suggested allowable associated channels
1	1,2	1,2,3
2	1,2,3	1,2,3,4
3	2,3,4	2,3,4,6,7
4	3,4,6	3,4,6,7
5	5,7	5,6,7
6	4,6,7	4,6,7
7	5,6,7	4,5,6,7

One can arrive at the same conclusions by computing the degree of orthogonality of weighting functions,

$$\int_{p_s}^{0} [d\tau(\nu_i,z,p)/d\log(p)][d\tau(\nu_j,z,p)/d\log(p)]d\log(p) / \int_{p_s}^{0} [d\log(p)].$$

This quantity will be near zero for $i=1$ and $j=5$, and will be unity for $i=j$. Intermediate values will reveal the interdependence of the channels. For further discussions of this topic see Twomey (1977).

VI. Procedures

There have been many procedures attempted, some of which were encouraging but which were still unsatisfactory. The best one was the use of latitudinal means.

Because the main purpose of the report is to provide a record for future use by personnel applying the principles and procedures to the operational satellite data, the following gives the steps in some considerable detail. Some of the information reflects the experience gained during the progress of the study.

A. Between 82N and 82S, count the data in each one-degree latitude belt for each surface type and each beam position; it is required that surface types must be identified at an earlier stage of the data processing. As noted elsewhere, coastlines are omitted, and it is better to do this at the outset. This gives 164 X 3 X 7 = 3444 data for the 164 latitudes, three surface types, and seven beam positions. Data already noted (bad data, flagged data, data with latitudes greater than 82 degrees, and coastlines) must be deleted. The counts should be entered into an array compatible with the array in the next step.

B. While counting the data, also add the radiance temperatures in an array, with the purpose of finding means later on. This array will contain 3444 X 7 = 24108 entries for the seven channels, although many of these (and 1/7 as many in the counting array) will contain no data.

C. For each channel and beam position, compute by regression the limb-adjustment coefficients from the relation, in the form of Eq. (2),

$$\overline{T}_{i0} = a_{i0k} + \sum_{j} (a_{ijk}\overline{T}_{ijk}), \tag{3}$$

where $\overline{T}$ is latitudinal mean temperature, i indicates the channel, j indicates the associated channel, k is the beam position, and a_{i0k} is the constant term. The least squares solutions use each surface type as an independent measure, so there are a possible 492 equations for the microwave (if there were all surface types at every latitude). The absence of data in some entries leaves about 320 data in each regression.

In matrix form, the above set of equations may be written

$$\underline{t}_{i0} = T_{ik}\underline{a}_{ik}. \tag{4}$$

Dimensions of the vector on the LHS will be N X 1; dimensions of the vector on the RHS will be (1+J) X 1; and dimensions of the matrix will be N X (1+J), where N is the total number of equations (several hundred); J is the number of associated channels. Elements of the column vector on the LHS are

$$\overline{T}_{i0n}-c,$$

in which the subscript 0 indicates the nadir view, n is the index associated with a latitude and surface type, and c is a constant (see below); row elements of the matrix T are unity and the J elements

$$\overline{T}_{ijkn} - c.$$

The solution is the usual least-squares matrix expression,

$$\underline{a}_{ik} = (T_{ik}^{*} T_{ik})^{-1} T_{ik}^{*} \underline{t}_{i0}, \tag{5}$$

where a superscript asterisk (*) indicates the transpose of the matrix.

The regression may take any of the standard forms: least squares; stepwise regression (in which the associated channels would be determined as part of the process); etc. In this study least squares has been used. If Eq. (5) is solved in a straightforward manner one finds nearly-singular matrices which cannot be inverted. To overcome this, one must subtract from each latitudinal mean temperature a quantity which will give a large relative range to the values (a process called centering). The most obvious quantity would be the global mean, obtained from an average of the latitudinal means. Here the arbitrary value of 250K was used. When the coefficients are found, the constant term is supplemented by subtracting the product of each of the channel coefficients times the amount originally subtracted.

It is necessary also to compute and save the standard deviations of the fits of the limb-adjusted data to the vertical values. That is, after the coefficients are found, compute the limb correction for each set of channel temperatures, given in the RHS of the Eq. 3 (this is the forward solution to Eq. 4); the difference between that value and the "true" value on the LHS is the deviation.

When Eq. (5) was first solved, each of the entries was weighted by the population of data in the subset. However, this led to significant systematic errors at the highest and lowest latitudinal means because they tended to be made from many fewer measurements. When each entry was given the same weight, these errors largely disappeared. Standard deviations for the unweighted computations are greater than those for the weighted computations. But physical realities require that the end points of a distribution must fit as well as the heavily populated central points; accuracy must take precedence over precision.

D. As a further control on the results, one should go through the computations a second time, deleting all those data which were outside the 3-σ limits after the first pass. For this use, the lowest standard deviation at any beam position for a given channel should be used for all beam positions. For each datum, compute the limb-adjusted value; if the absolute value of the difference between this and the vertical value exceeds 3-σ the datum is deleted in the second computation of coefficients. This eliminates latitudes where the data samples were too small, or where the sampling tends to bias beam positions differently, or where the surface type may be misclassified, or simply because the areas viewed at the different beam positions are systematically different despite the fact that the centers of the beams are the same. However, this effect is very small. When a datum is deleted on the 3-σ test, the datum for another channel may pass its test and should be used; this will be noted mainly when comparing window and non-window data, or tropospheric and stratospheric data. Data deleted by this test amounted to 1-4 percent of the total, depending on channel and beam position.

E. Updating. Because there may be instrument changes over time, and because a single sample may not contain a sufficient variety and range of measurements, it will be necessary from time to time to update the limb adjustment coefficients.

1. The latitudinal means, the coefficients, and the standard deviations should be kept for the life of the satellite. The older data will be used in combination with new data in generating new coefficients.

2. Nominally, the updating would be a seasonal affair, when there has been a major change in the weather patterns. However, other conditions should be kept in mind when preparing for an update. One of these is the period immediately after the onset of a major stratospheric warming, which normally takes place in the northern hemisphere in December. Another condition is a state of zonal flow at all levels of the atmosphere, when the variances in the latitudinal means are a minimum. Otherwise, updates should be scheduled for periods soon after the solstices and equinoxes.

3. The new data should be added to the old data, so the regressions will involve increasingly large dimensions. However, in the process, the data sets must be distinguished to determine if there are significant systematic differences among them. By some criteria not yet established, if the older data are different by some amount from the new data, the older data must be deleted and the coefficients recomputed with only the new data. There has not been an updating, so there are undoubtedly some factors which have not been considered.

F. Limb-adjustment coefficients for the first three satellites to carry the SSM/T, identified as F7, F8 and F9, have been computed by the methods presented here. Values of these coefficients are given in Appendices A, B and C, along with the standard deviations of fit and the numbers of latitudinal means used for each. It should be noted that:

1. Data for Channel 5 of satellite F7 are not accurate because the counts for the space view during calibrations were off scale. This does not affect the precision, but Channel 5 data cannot be used in an absolute sense.

2. The data for the F8 beam position #7 are unreliable because of

an obscuration on the satellite.

3. The coefficients for the F7 were determined from brightness temperatures after applying a precomputed set of coefficients to the antenna temperatures; the brightness temperatures were then matched according to the antisymmetric beam positions to eliminate biases. The coefficients for the F8 and F9 have been determined from antenna temperatures, with no adjustments.

VII. Significance of the latitudinal means

There is the question as to whether these latitudinal means represent individual sets of measurements or whether there are biases which are not found in the individual measurements. To verify the validity of the procedure, several tests have been conducted.

The F9 data were gone through once more, comparing each set of measurements with its respective means. The set of measurements which had the smallest mean deviation, defined as the sum of the absolute deviations (usually called the ℓ_1 norm), was found:

$$d_{kl} = \min_{m} \sum_{i} |T_{iklm} - \overline{T}_{ikl}|/7,$$

where i is the channel number, k is the beam position, l is latitude, and m is the index for sets of measurements comprising the means (using only those sets of observations entering into each set of means). Each set of means was tested against from 2 to 284 sets of measurements, with an average of 43.9; sets in which there had been a failure of the 3-σ test were not used. Fig. 3 shows a histogram of the 2061 best-fit mean deviations.

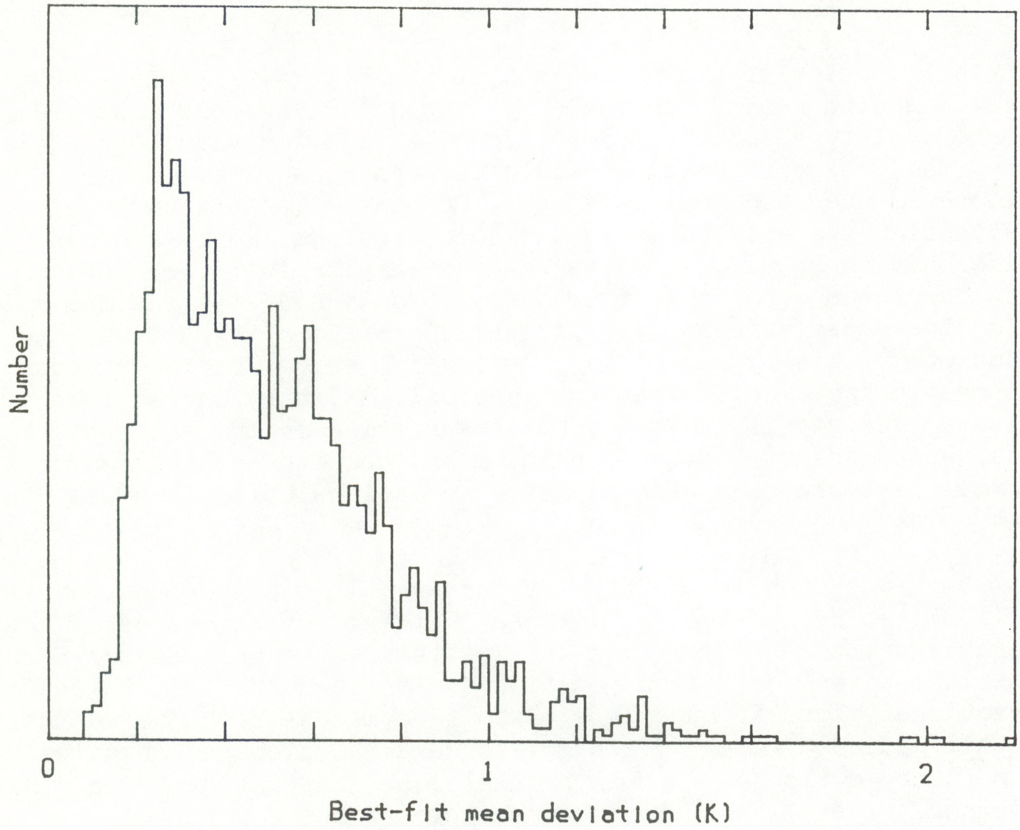

Figure 3. Histogram of the best-fit mean deviations for the F9 SSM/T latitudinal means. There are 2061 samples comprising the histogram.

A. In the worst case the best-fit mean deviation was 2.186 degrees. The fact that each mean passed the 3-σ test indicates that there were compensatory deviations in the sub-samples which produced physically reasonable means pertinent to the limb-adjustment algorithm.

B. Fig. 3 is a composite of the data from the three surface types. Examination of the individual surface types reveals the characteristics given in Table 4. Note from Table 5 in the next section that the expected mean deviation of a single set of observations, the square root of the mean squares of the listed RMS noise values, is 0.352 K.

Table 4. Characteristics of the F9 SSM/T best-fit mean deviations for the three surface types.

Surface	Mean d_{kl} (K)	Max. d_{kl} (K)	99% (K)	Ave. no. of obs.	No. of means
Water	.450	1.627	1.20	55.4	966
Land	.536	2.026	1.49	30.1	861
Ice	.678	2.186	1.41	47.5	234
Total	.512	2.186	1.38	43.9	2061

Next the behavior of the deviations of the best-fit sample of 2061 sets of observations with respect to their latitudinal means were examined. Figure 4 shows histograms of the deviations for the individual channels. It is apparent that, except for skewness in Channel 1, each of these distributions is nearly normal in shape, But there is an abundance of "outlyers", which are attributed to the polar regions and to oceanic observations having significant effects of precipitation; these data constitute about two percent of the total. Standard deviations are only about twice the noise values given in Table 5 in the next section, and the half-widths of the histograms at the 1/e levels, which are the standard deviatiations in normal distributions, are only slightly larger than the noise values. The significance of this figure lies in the fact that that these data, which are surrogates for the means used in the regressions, have nearly normal distributions with standard deviations compatible with the instrument noise.

Going back one step in the data processing, it was thought that it would be illuminating to examine histograms of the deviations of all of the measured radiance temperatures from the latitudinal means. Figure 5 shows histograms in the vertical (beam position 4) for each channel, taken from the observations by the F9 satellite; data from means which failed the 3-σ test were not included. Each of the histograms shows characteristics similar to those in Figure 4. Most channels are somewhat skewed and have varying degrees of "outlyers" beyond the expectations for normal distributions. Standard deviations of these distributions are 7.06, 3.31, 1.39, 1.14, 1.29, 1.62, and 1.44 1.1 degrees K. If one divides these values by the square root of 43.9, the average number of data in each mean, one

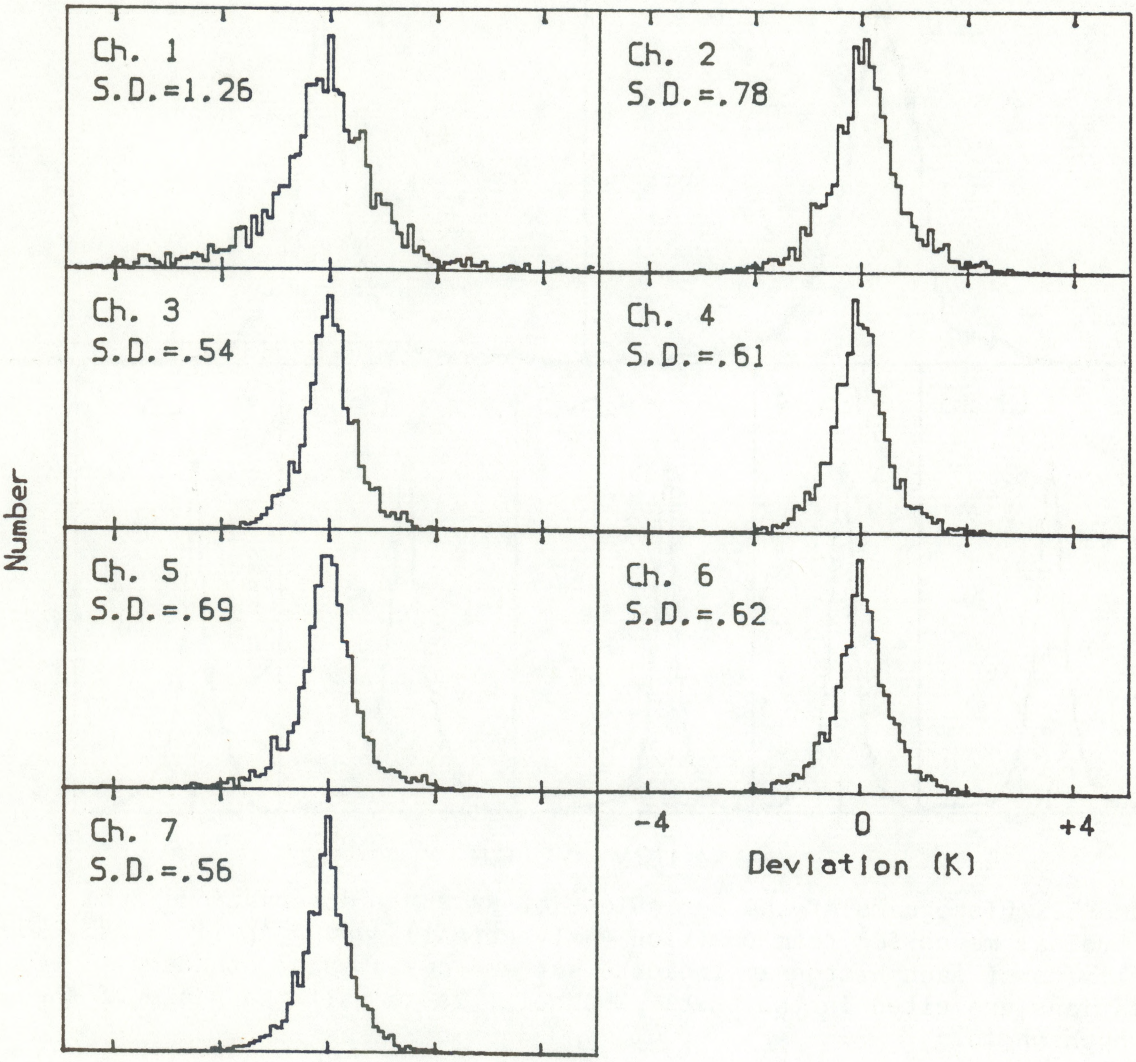

Figure 4. Histograms of deviations of best-fit F9 SSM/T observations from latitudinal means during April 18-24, 1988. The abscissae are marked in 2-degree intervals.

finds estimated errors of the means to be 1.07, 0.50, 0.21, 0.17, 0.19, 0.24 and 0.22 degrees K, which agree well with the standard deviations of fit given in Appendix C, and which, for channels not influenced by the surface, compare well with the noise. This implies that the latitudinal means are approximately equivalent to sets of individual measurements having instrumental noise, with some additional variability in Channels 1 and 2.

The conclusions from these tests are that the means do indeed represent individual sets of measurements, they reflect true limb variations at the seven beam positions, and the limb-adjustment coefficients derived from them are optimum, within the noise limitations, for the algorithm employed.

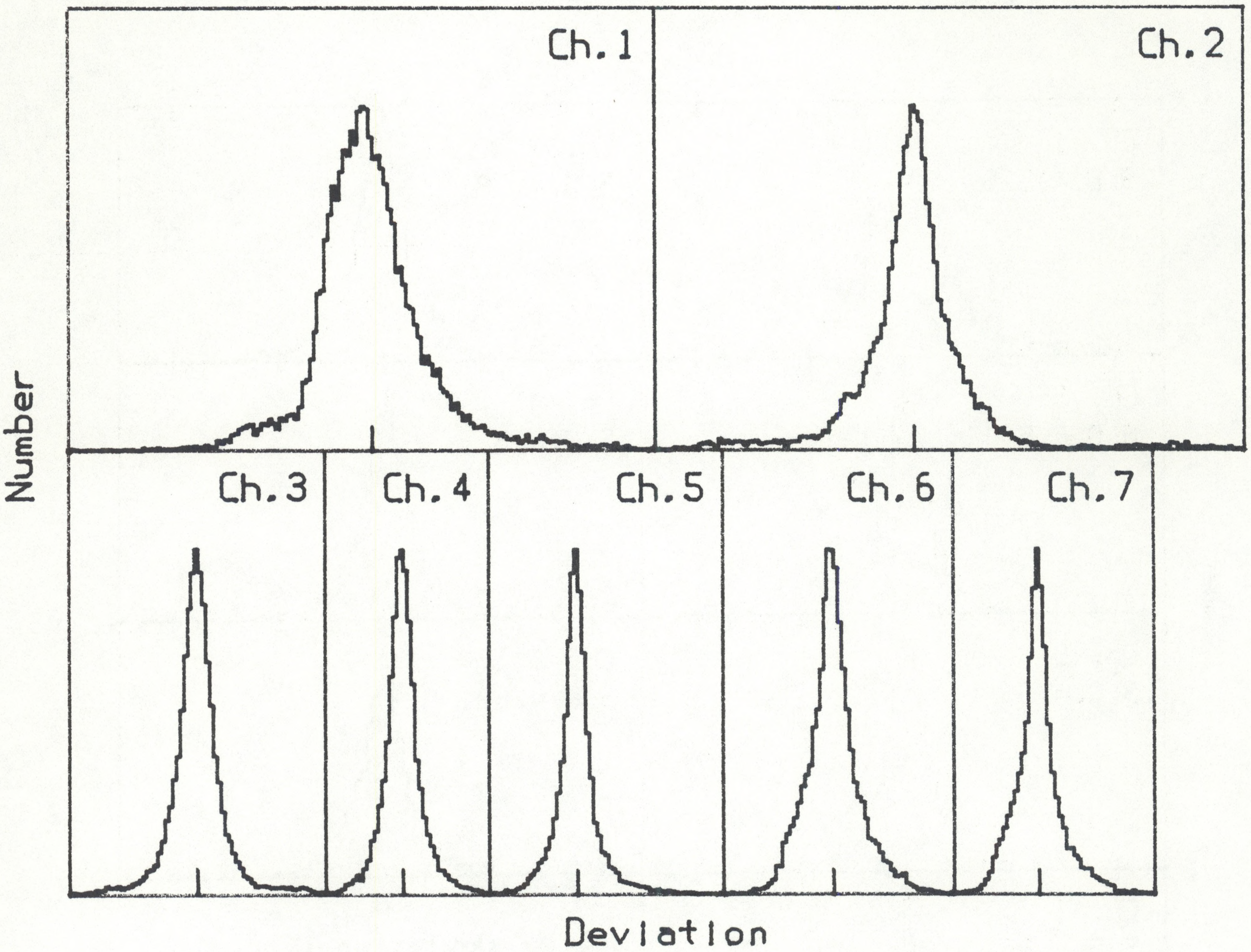

Figure 5. Histograms of the deviations of F9 SSM/T observations from latitudinal means for beam position #4 (vertical) during April 18-24, 1988. The limits of each histogram indicate extreme deviations; standard deviations are cited in the text. Channel 1 is at half the scale of the other channels.

VIII. Errors

There are two main sources of errors in the limb-adjusted radiance temperatures. One results from the amplification of the instrumental noise in the individual channels through multiplication by the coefficients. The other arises from errors in the coefficients, which is part of the least-squares process used in their derivation.

A. Noise.

Each measurement of radiance has, in addition to the signal, a random electrical noise. For the F9 SSM/T instrument the noise has standard deviations of about 0.2-0.5 K (see Table 5 below).

Limb adjustments have the potential for amplifying the noise, depending upon the magnitude of the channel coefficients. It is obvious that the standard deviation of a limb-adjusted measurement for channel i at beam position k will be

$$\sigma_{ik} = [\sum_j (a_{ijk}\sigma_j)^2]^{1/2}. \tag{6}$$

Applying Eq. (6) to the coefficients for satellite F9 given in Appendix C and to the RMS noise values given in the second column of Table 7, we find the factors by which the channel noise values are multiplied; their values are given in the remaining columns of Table 5. Channels 4, 5, and 7 become less noisy after limb adjustment, while Channels 1, 2, 3, and 6 become more noisy.

Table 5. Noise and factors of noise amplification (greater than unity) or noise reduction (less than unity) for the SSM/T on the F9 satellite. Noise figures are averaged over two orbits during June 29-30, 1988.

Ch.	RMS	Beam position						
	noise	1	2	3	4	5	6	7
1	0.512	1.523	1.123	1.022	1	1.014	1.109	1.495
2	0.392	1.013	1.017	1.002	1	1.009	1.014	1.017
3	0.356	1.136	1.065	1.014	1	1.017	1.094	1.193
4	0.402	0.657	0.780	0.927	1	0.927	0.819	0.669
5	0.244	0.922	0.968	0.990	1	0.989	0.965	0.922
6	0.169	1.432	1.126	1.027	1	1.036	1.142	1.459
7	0.276	0.713	0.854	0.933	1	0.960	0.829	0.653

The effects of the increased noise in Channels 1, 2, 3, and 6 are not considered to be serious because:

1. The increased noise in Channel 1 has virtually no effect on

temperature retrievals, because this channel is not used except as a precipitation indicator for the SSM/T. For other instruments, such as the AMSU, this channel will be used to aid in determining certain surface properties, as well as estimating rainfall rates. For these purposes, the increased noise will have negligible adverse effects on the products, and limb adjustment will have many benefits.

2. The increase in noise for Channel 2 (less than 0.01 K) is too small to be significant.

3. Channel 3 is situated in the middle troposphere, as seen in Figure 1. For this reason, the increased noise has the effect of increasing the noise in the retrievals in that portion of the atmosphere. However, this has been shown to be the most stable and reliable portion of the retrievals, and the added noise will have only a similar effect (less than 0.1 K) on the middle tropospheric temperature, which is certainly an acceptable value.

4. The larger fractional increase in noise in Channel 6 is partly offset by the low electrical noise. The increase of nearly 0.1K is unlikely to have a significant effect because this channel behaves in the lower stratosphere in much the same way as Channel 3 in the troposphere. The reason for the magnitude of the increase is the absence of a channel immediately below it in the atmosphere (see the vertical gap between Channels 4 and 6 in Figure 1). This phenomenon will not occur with the AMSU, which has more numerous and closely spaced channels.

It would be safe to say that some of the SSM/T channels become more noisy in the limb-adjustment process, but that the magnitude of the noise is within tolerable limits.

B. Errors of estimate.

The other factor leading to errors in the limb-adjusted radiance temperatures involves the errors in the coefficients. Standard deviations computed in section VI are a measure of the unreliability of the coefficients; values are given in the next to last table of each appendix. The reason for the greater standard deviations in some of the F7 channels is the presence of greater variations in the stratosphere of the southern hemisphere, whereas at the time of the observations by the F8 and F9 satellites the stratosphere had a more zonal flow.

However, the standard deviations of fit do not, by themselves, give quantitative estimates of the errors in the coefficients or of the errors in the limb adjustments induced by the errors in the coefficients.

It can be shown (Neter, et al., 1983) that for a well-behaved sample having near-normal distributions, the estimated covariance matrix of coefficient errors for Channel i at beam position k is

$$s^2(\underline{a}_{ik}) = MSE_{ik}(T_{ik}^{*}T_{ik})^{-1}, \tag{7}$$

where a, i, k, and T have the same meanings as in Eq. (5), and MSE is the estimated variance, the square of the standard deviation given in the next to last table of each appendix. The square roots of the diagonal elements are the standard deviations (errors) of estimate for the individual coefficients. The channel coefficients are, in every case, on the order of 0.01, which means that consideration of the products of these coefficients and the deviations may be neglected. It remains only to show how the errors in the coefficients act in concert to induce errors in the limb-adjusted radiance temperatures.

If the row vector $\underline{x}_{ikn}$ represents the terms in row n of the matrix T_{ik} of Eq. (4), or

$$\underline{x}_{ikn} = (1, T_{i1kn}, \ldots, T_{iJkn}), \tag{8}$$

where J is the number of associated channels, then it can be shown (Neter, et al., 1983) that the estimated error for the limb-adjusted value of the observation given in row n is

$$e_{ikn} = [MSE_{ik}\underline{x}_{ikn}(T_{ik}^{*}T_{ik})^{-1}\underline{x}_{ikn}^{*}]^{1/2}. \tag{9}$$

Applying Eq. (9) to the F9 latitudinal means, the estimated errors resulting from errors in the coefficients were evaluated. It does not matter that overall means were subtracted from the latitudinal means when forming the vectors and matrices. Table 6 gives the average and maximum estimated errors for each channel and each beam position.

Table 6. Average and maximum estimated errors (degrees K) of SSM/T limb-adjusted latitudinal means from the F9 spacecraft caused by the errors of estimate of the coefficients.

	Beam position						
Ch.	1	2	3	4	5	6	7
1	.146/.281	.119/.230	.110/.206	0	.100/.188	.122/.232	.140/.279
2	.061/.165	.051/.154	.050/.136	0	.047/.131	.054/.140	.057/.140
3	.027/.066	.022/.055	.020/.048	0	.021/.051	.024/.063	.025/.074
4	.024/.053	.024/.052	.021/.046	0	.022/.051	.022/.054	.023/.059
5	.021/.040	.018/.033	.017/.032	0	.018/.034	.020/.040	.025/.052
6	.027/.058	.026/.060	.022/.053	0	.023/.055	.025/.058	.029/.065
7	.025/.042	.023/.039	.023/.040	0	.022/.039	.023/.041	.025/.047

From the values in Tables 5 and 6 it can be seen that the mean error for Channel 1 is about 24 percent of the noise, and for the other channels the mean error is 6-17 percent of the noise. The maxima are, in all cases, less than 55 percent of the noise, and in most channels and beam positions the errors are entirely negligible. Thus, even though these errors are systematic, they have little effect on the limb adjustments. Inasmuch as it has already been shown that the latitudinal means are representive of individual measurements, the errors for the latter must be about the same as those demonstrated here for the former.

From these two assesssments of errors, it must be concluded that, from any cause, they are either small or of no consequence.

IX. Applications to other sounding instruments

A. The Advanced Microwave Sounding Unit (AMSU)

The AMSU will be carried on the NOAA series of satellites beginning in about 1992 or 1993. One of the instruments, the AMSU-A, will have 15 channels which provide three additional windows, greater range in the stratosphere, and a somewhat different arrangement of tropospheric channels. The AMSU-B will have a common window channel with the AMSU-A, plus four channels in the 183 GHz line of water vapor.

1. The data sample must be the same as for the SSM/T. That is, several days of data are required, bad data must be detected and omitted, and high latitude data must be omitted. The criterion for high latitude will be the same as the SSM/T, about 82 degrees.

2. For the AMSU data the same divisions of surface type as used for the SSM/T will apply.

3. Global limb adjustments are made on the archive of accepted data at the locations of the AMSU-A spots. This means that all data in the stage immediately prior go limb adjustments must be saved, but some will be flagged as unacceptable (this should take care of the cloud problems in the more transparent channels).

4. The definitions of associated channels are not complete at this time. However, the plan is to use the channel immediately above and immediately below in the atmosphere. This poses a special problem for water vapor channels; and it may be necessary to use more than three channels with these data. There is also likely to be an exception with the several window channels, where the differences result mainly from the surface characteristics; the final selection of channels in these cases is likely to be made only after the launch of the first instruments. There is no plan to use combinations of HIRS-2I and AMSU data.

5. For the AMSU there is no vertical beam position. However, an average of the two beam positions on each side of the nadir will provide a good estimate. Because radiances vary approximately as the secant of the local zenith angle, errors induced from this averaging will be about two orders of magnitude smaller than the noise. For the AMSU-A the secant is about 1.0004. When this factor is multiplied by the maximum limb effect possible at $z=60$ degrees, about 10 percent, the error becomes 0.1K; this value is exaggerated, and in every case it is likely to be smaller.

B. The High-resolution InfraRed Sounder, Model 2, Improved (HIRS-2I)

1. For the HIRS-2I data, no division into surface type is required.

2. Local limb adjustments (small adjustments to a set of fixed

angles).

a. All data must be used, regardless of cloudiness. This is because the data will not have been subjected to the cloud-clearing process.

b. For each AMSU beam position there will be several HIRS-2I beam positions to be adjusted to it. To put it another way, there will be separate adjustments of each HIRS-2I beam position to several AMSU beam positions. Although this has not been tested, it may be possible to evaluate the coefficients for the separate beam positions as a closed expression in 1-sec(z).

c. Because clouds occur at various heights in the atmosphere, more channels are needed for limb-adjustments. No study of the optimum associated channels for conditions with clouds present has been made.

3. Global limb adjustments for the HIRS-2I are made in the same way as the AMSU. Only cloud-cleared data are used, and the locations are identical with those of the AMSU.

4. The HIRS-2I, like the AMSU, has no vertical view, so an average of the two views on each side of the nadir should act as the true nadir value. The secant of the zenith angle at these positions is about 1.0001, and the greatest error likely at the extreme viewing angle should be less than 0.05K.

5. There are several advantages to using radiance temperatures with the HIRS-2I, rather than radiances. However, this may be done only for the global limb adjustments; for the local limb adjustments the radiances are required.

C. The Stratospheric Sounding Unit (SSU)

This is a three-channel instrument with channels covering the the stratosphere to about 2 mb. There are no special requirements for the data from this instrument, and it may be handled in much the same way as the global limb corrections for the HIRS-2I. No tests of data have been conducted, so possible problem areas are not apparent. The most likely need would be for use of some HIRS-2I upper-level channels, colocated with the SSU data, to act as associated channels. It is suggested that radiance temperatures, rather than radiances, be used.

D. The Microwave Sounding Unit (MSU)

Data from this instrument have been subjected to a small study, using a sample of only one day of data. The results, while not bad, were not satisfactory. The most important evidence that turned up is that there are simply not enough MSU channels to make a satisfactory limb adjustment for all channels. This has been pointed out by D.

Staelin (private communication). Channel 4 was particularly deficient near the South Pole because Channel 2 was required as an associated channel to force a reduction of standard deviations of fit to reasonable proportions. The conclusion is that the MSU must be limb-adjusted using supplementary infrared data from the HIRS-2I and the SSU.

X. Note on updating

Prior to publication of this document there was an opportunity to update the coefficients for the F8 and F9 satellites. Data were taken during July 21-28, 1988, when the norther hemisphere was in mid-summer and the southern hemisphere was in mid-winter. Following the procedures of section VI, new coefficients were obtained from latitudinal means obtained during both observational periods. These data, representing two seasons, doubled the dimension N in Eqs. (4) and (5). The results are given in Appendices D and E.

Most of the coefficients exhibit substantial changes after the update, but each change tends to be compensated by a contrary change in other coefficients. For the F9 satellite the coefficients tend to become more symmetric about the nadir, suggesting that the instrument performs that way and that the new coefficients are indeed improved. The only discernible biases were at beam position 1 for Channel 1, where data from the Spring/Fall period had systematic deviations of about -1/2 degree K over the southern oceans. This is attributed to the absence of a water vapor channel, such as the one with the AMSU, to be used as a predictor; there are significant seasonal variations in water vapor which are emphasized in Channel 1 over the oceans. Biases were determined by visual inspection rather than by an objective test.

Standard deviations of fit were slightly larger than the values given in Appendices B and C, caused mainly by the greater longitudinal variances in the July measurements over the southern hemisphere. There were about the same number of data deleted by the 3-σ test. The range of values of the latitudinal means was increased by a few percent for Channel 1 to as much as a factor of three for Channel 4, which assures improved limb adjustments for extreme radiance temperatures.

Results for the F8 satellite are similar to those for the F9 satellite, and in some channels the improvements were even superior because the earlier period was nearer in time to the Vernal Equinox. Beam position 7 is not used.

To show the impact of the updating, measurements taken during a 24-hour period from the SSM/T on satellite F9 were limb-adjusted, using both the old and the new coefficients, and root-mean-square (RMS) differences of the results were computed at each beam position for each channel. These values are given in Table 7. The numbers in this table are, in some cases, comparable to the mean estimated errors given in Table 6. In other cases, notably Channel 4, the larger values result from better estimates of the limb adjustments based on greater ranges of the latitudinal means. The larger values for Channel 1 are the result of the biases noted above. There is no explanation for the anomaly in Channel 3, beam position 7, other than a deficiency in the earlier coefficients; a positive bias with the earlier coefficients is confined almost exclusively to the region south of 50 south latitude, which is indicative of an improvement in the updated coefficents.

The evidence from the results given here suggests that the instrument was extremely stable from one observational period to the other. Further, the updating process is a beneficial exercise to improve the estimates of limb adjustments.

Table 7. Root-mean-square (RMS) differences (degreees K) between limb-adjusted F9 SSM/T data computed from the original and the updated sets of coefficients. Data are taken from July 26-27, 1988.

	Beam position						
Channel	1	2	3	4	5	6	7
1	.574	.118	.025	0	.106	.040	.567
2	.100	.031	.010	0	.097	.040	.029
3	.017	.129	.049	0	.098	.111	.338
4	.233	.160	.091	0	.152	.157	.275
5	.160	.088	.023	0	.070	.083	.108
6	.126	.129	.097	0	.041	.048	.185
7	.119	.070	.026	0	.015	.061	.037

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Appendix A. Limb-adjustment coefficients for SSM/T, satellite F7.

Beam position #1

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	44.42	1.41040	-0.59692	0	0	0	0	0
2	-1.99	0.10257	0.99226	-0.07769	0	0	0	0
3	-1.12	0	0.09090	1.17673	-0.25685	0	0	0
4	2.94	0	0	0.42969	0.60034	0	-0.04181	0
5	14.49	0	0	0	0	0.84524	0	0.09105
6	19.48	0	0	0	0.05786	0	1.45416	-0.59998
7	36.40	0	0	0	0	-0.13666	0.27441	0.70276

Beam position #2

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	10.28	1.10172	-0.14165	0	0	0	0	0
2	1.51	0.03496	1.02609	-0.06609	0	0	0	0
3	-1.09	0	0.03667	1.07318	-0.10301	0	0	0
4	1.18	0	0	0.18585	0.81921	0	-0.01065	0
5	10.16	0	0	0	0	0.92365	0	0.03183
6	9.73	0	0	0	0.05249	0	1.22046	-0.31812
7	25.13	0	0	0	0	-0.10071	0.07251	0.91663

Beam position #3

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	1.22	1.01636	-0.02020	0	0	0	0	0
2	-0.33	0.00828	1.00210	-0.00931	0	0	0	0
3	-0.27	0	0.00740	1.01990	-0.02567	0	0	0
4	0.76	0	0	0.05621	0.93646	0	0.00372	0
5	6.49	0	0	0	0	0.97080	0	0.00048
6	0.94	0	0	0	0.00610	0	1.03601	-0.04663
7	4.73	0	0	0	0	-0.02271	0.01013	0.99170

Beam position #4

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	0.00	1.00000	0	0	0	0	0	0
2	0.00	0	1.00000	0	0	0	0	0
3	0.00	0	0	1.00000	0	0	0	0
4	0.00	0	0	0	1.00000	0	0	0
5	0.00	0	0	0	0	1.00000	0	0
6	0.00	0	0	0	0	0	1.00000	0
7	0.00	0	0	0	0	0	0	1.00000

Beam position #5

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	3.72	1.00929	-0.02405	0	0	0	0	0
2	0.66	0.00393	1.00197	-0.00818	0	0	0	0
3	0.74	0	0.00840	1.01791	-0.02930	0	0	0
4	1.25	0	0	0.06909	0.91528	0	0.00897	0
5	17.57	0	0	0	0	0.93660	0	-0.01446
6	4.68	0	0	0	0.02203	0	1.07532	-0.11914
7	11.04	0	0	0	0	-0.04633	-0.01306	1.01086

Appendix A (continued).

Beam position #6

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	12.01	1.08444	-0.13270	0	0	0	0	0
2	1.89	0.02858	1.01629	-0.05017	0	0	0	0
3	-0.03	0	0.02512	1.10376	-0.12614	0	0	0
4	2.14	0	0	0.17255	0.84045	0	-0.02252	0
5	9.71	0	0	0	0	0.94394	0	0.01144
6	9.57	0	0	0	0.03244	0	1.19214	-0.26880
7	20.94	0	0	0	0	-0.07599	0.08130	0.90186

Beam position #7

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	40.22	1.34433	-0.51579	0	0	0	0	0
2	4.98	0.08056	1.03115	-0.12705	0	0	0	0
3	2.73	0	0.08389	1.19208	-0.28223	0	0	0
4	3.90	0	0	0.44940	0.55579	0	-0.02148	0
5	3.96	0	0	0	0	0.89831	0	0.08217
6	20.37	0	0	0	0.03696	0	1.40790	-0.53748
7	32.58	0	0	0	0	-0.11237	0.25696	0.71130

Standard deviations of fit (degrees K)

	Beam position						
Ch.	1	2	3	4	5	6	7
1	1.5547	1.3930	1.2831	0	1.1627	1.4243	1.5633
2	0.5544	0.5082	0.4988	0	0.5006	0.5466	0.5638
3	0.2675	0.2479	0.2377	0	0.2632	0.2729	0.2369
4	0.2271	0.2015	0.2351	0	0.2132	0.2169	0.2245
5	0.5655	0.5812	0.5340	0	0.5491	0.5702	0.5498
6	0.5088	0.4575	0.4486	0	0.4465	0.4575	0.4744
7	0.5217	0.4657	0.4684	0	0.4797	0.4877	0.4920

Numbers of data used to compute coefficients

	Beam position						
Ch.	1	2	3	4	5	6	7
1	302	310	315	0	314	305	291
2	302	306	314	0	316	302	299
3	308	306	311	0	314	310	300
4	301	308	311	0	306	303	300
5	308	313	312	0	313	308	305
6	304	311	312	0	307	305	299
7	306	309	313	0	308	305	302

Appendix B. Limb-adjustment coefficients for SSM/T, satellite F8.

Beam position #1

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	64.06	1.44169	-0.70016	0	0	0	0	0
2	28.67	0.09597	1.06670	-0.28213	0	0	0	0
3	17.57	0	0.11530	1.10768	-0.29510	0	0	0
4	15.63	0	0	0.40894	0.56042	0	-0.03644	0
5	-2.37	0	0	0	0	0.90878	0	0.10382
6	6.69	0	0	0	0.01314	0	1.34589	-0.38751
7	5.21	0	0	0	0	-0.03174	0.34106	0.66992

Beam position #2

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	16.30	1.11194	-0.17397	0	0	0	0	0
2	-0.52	0.03779	0.99515	-0.02588	0	0	0	0
3	8.61	0	0.04321	1.06866	-0.14734	0	0	0
4	13.71	0	0	0.20441	0.73663	0	-0.00212	0
5	0.97	0	0	0	0	0.95772	0	0.03924
6	2.87	0	0	0	0.00076	0	1.13879	-0.15125
7	3.22	0	0	0	0	-0.02026	0.13452	0.87305

Beam position #3

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	4.28	1.01988	-0.03541	0	0	0	0	0
2	-4.41	0.01374	0.97012	0.03816	0	0	0	0
3	8.43	0	0.01439	1.01529	-0.06653	0	0	0
4	14.42	0	0	0.08084	0.84909	0	0.00519	0
5	3.03	0	0	0	0	0.98389	0	0.00297
6	11.14	0	0	0	-0.04480	0	1.01215	-0.01654
7	1.36	0	0	0	0	-0.00806	0.03052	0.97217

Beam position #4

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	0.00	1.00000	0	0	0	0	0	0
2	0.00	0	1.00000	0	0	0	0	0
3	0.00	0	0	1.00000	0	0	0	0
4	0.00	0	0	0	1.00000	0	0	0
5	0.00	0	0	0	0	1.00000	0	0
6	0.00	0	0	0	0	0	1.00000	0
7	0.00	0	0	0	0	0	0	1.00000

Beam position #5

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	1.50	1.01049	-0.01607	0	0	0	0	0
2	-7.39	0.00960	0.95982	0.06594	0	0	0	0
3	-0.53	0	-0.00043	1.04208	-0.03815	0	0	0
4	13.16	0	0	0.07141	0.87341	0	-0.00417	0
5	-1.78	0	0	0	0	0.99121	0	0.01729
6	14.99	0	0	0	-0.04799	0	1.02142	-0.04053
7	1.22	0	0	0	0	0.00769	0.06543	0.92139

Appendix B (continued).

Beam position #6

Ch.	Const.	Channel 1	2	3	4	5	6	7
1	18.10	1.09282	-0.16279	0	0	0	0	0
2	-16.29	0.03696	0.92360	0.11958	0	0	0	0
3	-2.60	0	0.00843	1.14450	-0.13721	0	0	0
4	16.18	0	0	0.19333	0.74707	0	-0.01221	0
5	-0.45	0	0	0	0	0.95801	0	0.04498
6	21.77	0	0	0	-0.07772	0	1.13062	-0.14929
7	0.77	0	0	0	0	0.00049	0.18115	0.81616

Beam position #7

Ch.	Const.	Channel 1	2	3	4	5	6	7
1	37.98	1.51574	-0.66236	0	0	0	0	0
2	-1.18	0.09145	1.15902	-0.23683	0	0	0	0
3	16.85	0	0.09225	1.36179	-0.52365	0	0	0
4	37.96	0	0	0.56812	0.27618	0	-0.01450	0
5	-20.06	0	0	0	0	1.04991	0	0.04187
6	61.10	0	0	0	-0.29120	0	1.35242	-0.33203
7	-17.55	0	0	0	0	0.08777	0.43018	0.56445

Standard deviations of fit (degrees K)

Ch.	Beam position 1	2	3	4	5	6	7
1	1.8312	1.7257	1.6281	0	1.4926	1.8055	1.9513
2	0.6248	0.6542	0.6885	0	0.6127	0.6741	0.6626
3	0.2506	0.2646	0.2648	0	0.2420	0.2927	0.3105
4	0.2194	0.2322	0.2063	0	0.2301	0.2683	0.3015
5	0.3634	0.3873	0.4008	0	0.3621	0.4318	0.4718
6	0.3929	0.3575	0.3673	0	0.3181	0.3524	0.4790
7	0.3266	0.2926	0.3141	0	0.2800	0.3152	0.4117

Numbers of data used to compute coefficients

Ch.	Beam position 1	2	3	4	5	6	7
1	296	307	312	0	315	301	299
2	298	307	310	0	316	304	293
3	301	306	310	0	318	307	289
4	296	307	309	0	318	309	293
5	300	306	313	0	314	305	295
6	302	305	312	0	313	306	297
7	302	306	310	0	311	303	297

Appendix C. Limb-adjustment coefficients for SSM/T, satellite F9.

Beam position #1

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	59.40	1.43278	-0.67409	0	0	0	0	0
2	-2.39	0.10089	1.00227	-0.08018	0	0	0	0
3	0.74	0	0.12326	1.10037	-0.21869	0	0	0
4	7.36	0	0	0.43094	0.53406	0	0.00592	0
5	-1.27	0	0	0	0	0.91631	0	0.09207
6	7.59	0	0	0	-0.04041	0	1.33014	-0.31952
7	-0.98	0	0	0	0	-0.01855	0.34619	0.68164

Beam position #2

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	13.86	1.11448	-0.16707	0	0	0	0	0
2	-0.70	0.03699	1.01548	-0.04567	0	0	0	0
3	-2.98	0	0.04353	1.05981	-0.08679	0	0	0
4	5.98	0	0	0.20020	0.75977	0	0.01376	0
5	-0.19	0	0	0	0	0.96685	0	0.03490
6	7.48	0	0	0	-0.04626	0	1.10938	-0.09521
7	-1.22	0	0	0	0	0.00110	0.15674	0.84888

Beam position #3

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	1.29	1.02202	-0.02590	0	0	0	0	0
2	-0.55	0.00941	1.00173	-0.00759	0	0	0	0
3	-1.28	0	0.01167	1.01402	-0.01918	0	0	0
4	3.25	0	0	0.05475	0.92615	0	0.00458	0
5	0.23	0	0	0	0	0.98997	0	0.00931
6	3.45	0	0	0	-0.01392	0	1.02515	-0.02637
7	0.33	0	0	0	0	0.00854	0.05737	0.93262

Beam position #4

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	0.00	1.00000	0	0	0	0	0	0
2	0.00	0	1.00000	0	0	0	0	0
3	0.00	0	0	1.00000	0	0	0	0
4	0.00	0	0	0	1.00000	0	0	0
5	0.00	0	0	0	0	1.00000	0	0
6	0.00	0	0	0	0	0	1.00000	0
7	0.00	0	0	0	0	0	0	1.00000

Beam position #5

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	3.61	1.01361	-0.02692	0	0	0	0	0
2	2.84	0.00690	1.00838	-0.02672	0	0	0	0
3	2.58	0	0.01081	1.01591	-0.03764	0	0	0
4	4.39	0	0	0.05331	0.92511	0	0.00174	0
5	1.09	0	0	0	0	0.98899	0	0.00629
6	-1.06	0	0	0	0.01001	0	1.03308	-0.03809
7	0.08	0	0	0	0	0.00195	0.04150	0.95654

Appendix C (continued).

Beam position #6

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	14.83	1.10203	-0.15952	0	0	0	0	0
2	1.29	0.03267	1.01173	-0.04625	0	0	0	0
3	3.11	0	0.03289	1.08423	-0.12868	0	0	0
4	5.55	0	0	0.17484	0.80457	0	-0.00406	0
5	1.41	0	0	0	0	0.96395	0	0.03003
6	4.48	0	0	0	-0.01892	0	1.12323	-0.12341
7	-0.55	0	0	0	0	0.00879	0.17188	0.82227

Beam position #7

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	59.06	1.40935	-0.65229	0	0	0	0	0
2	5.83	0.09348	1.00468	-0.11440	0	0	0	0
3	10.68	0	0.09990	1.14294	-0.28555	0	0	0
4	8.35	0	0	0.40924	0.56189	0	-0.00760	0
5	0.66	0	0	0	0	0.91727	0	0.07852
6	8.08	0	0	0	-0.03748	0	1.34480	-0.34235
7	-0.99	0	0	0	0	0.00537	0.39307	0.60693

Standard deviations of fit (degrees K)

	Beam position						
Ch.	1	2	3	4	5	6	7
1	1.4655	1.2009	1.1322	0	1.0276	1.2381	1.3662
2	0.5280	0.4521	0.4471	0	0.4188	0.4730	0.4993
3	0.2306	0.1939	0.1811	0	0.1878	0.2098	0.2196
4	0.2116	0.2101	0.1860	0	0.1954	0.1930	0.2040
5	0.2083	0.1777	0.1753	0	0.1819	0.1972	0.2466
6	0.2345	0.2291	0.1977	0	0.1993	0.2143	0.2462
7	0.2193	0.2005	0.2059	0	0.1932	0.2018	0.2142

Numbers of data used to compute coefficients

	Beam position						
Ch.	1	2	3	4	5	6	7
1	303	310	320	0	316	310	288
2	304	311	319	0	315	311	307
3	305	309	315	0	317	314	310
4	309	310	317	0	319	313	307
5	302	309	320	0	318	307	303
6	301	308	319	0	311	306	292
7	305	310	320	0	311	308	303

Appendix D. Updated limb-adjustment coefficients for SSM/T, satellite F8.

Beam position #1

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	52.23	1.42710	-0.64001	0	0	0	0	0
2	0.17	0.09727	0.98817	-0.07518	0	0	0	0
3	1.31	0	0.10271	1.14264	-0.24377	0	0	0
4	-0.07	0	0	0.42865	0.60132	0	-0.02658	0
5	-3.13	0	0	0	0	0.91117	0	0.10450
6	2.12	0	0	0	0.01660	0	1.35037	-0.37469
7	1.37	0	0	0	0	-0.00977	0.37549	0.63025

Beam position #2

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	13.65	1.10589	-0.15788	0	0	0	0	0
2	-1.54	0.03460	0.99984	-0.02337	0	0	0	0
3	-0.37	0	0.03558	1.07721	-0.10760	0	0	0
4	1.17	0	0	0.19678	0.79834	0	0.00021	0
5	0.15	0	0	0	0	0.95835	0	0.04219
6	2.00	0	0	0	-0.00824	0	1.12579	-0.12524
7	0.21	0	0	0	0	-0.00989	0.14331	0.86719

Beam position #3

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	3.06	1.01642	-0.02737	0	0	0	0	0
2	-1.20	0.01000	0.98809	0.00899	0	0	0	0
3	0.19	0	0.01056	1.01019	-0.02039	0	0	0
4	1.19	0	0	0.06363	0.92218	0	0.00896	0
5	0.72	0	0	0	0	0.98749	0	0.00978
6	3.02	0	0	0	-0.02045	0	1.01154	-0.00378
7	0.62	0	0	0	0	0.00146	0.04834	0.94788

Beam position #4

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	0.00	1.00000	0	0	0	0	0	0
2	0.00	0	1.00000	0	0	0	0	0
3	0.00	0	0	1.00000	0	0	0	0
4	0.00	0	0	0	1.00000	0	0	0
5	0.00	0	0	0	0	1.00000	0	0
6	0.00	0	0	0	0	0	1.00000	0
7	0.00	0	0	0	0	0	0	1.00000

Beam position #5

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	1.64	1.01300	-0.01892	0	0	0	0	0
2	-1.91	0.00862	0.98128	0.02060	0	0	0	0
3	-0.51	0	-0.00017	1.04060	-0.03700	0	0	0
4	0.69	0	0	0.05762	0.93658	0	0.00287	0
5	-0.17	0	0	0	0	0.98906	0	0.01207
6	0.75	0	0	0	0.00006	0	1.02716	-0.03040
7	-0.33	0	0	0	0	0.01184	0.06104	0.92847

Appendix D (continued).

Beam position #6

Ch.	Const.	Channel 1	2	3	4	5	6	7
1	15.81	1.09924	-0.15974	0	0	0	0	0
2	0.81	0.03301	1.00204	-0.03387	0	0	0	0
3	0.53	0	0.01741	1.12750	-0.14348	0	0	0
4	1.25	0	0	0.19055	0.80725	0	-0.00220	0
5	-0.06	0	0	0	0	0.95617	0	0.04521
6	1.41	0	0	0	-0.00177	0	1.15094	-0.15381
7	-0.06	0	0	0	0	0.00732	0.19714	0.79700

Beam position #7

Ch.	Const.	Channel 1	2	3	4	5	6	7
1	40.23	1.53055	-0.68680	0	0	0	0	0
2	-0.98	0.09663	1.10845	-0.18898	0	0	0	0
3	-4.46	0	0.09477	1.30713	-0.37366	0	0	0
4	-4.61	0	0	0.56128	0.45227	0	0.00958	0
5	-17.22	0	0	0	0	1.03330	0	0.04535
6	4.83	0	0	0	-0.13165	0	1.33536	-0.21802
7	-18.98	0	0	0	0	0.18445	0.66980	0.23059

Standard deviations of fit (degrees K)

Ch.	Beam position 1	2	3	4	5	6	7
1	1.8451	1.6837	1.5397	0	1.4951	1.7078	1.8938
2	0.6123	0.6440	0.6469	0	0.6035	0.6691	0.7145
3	0.2707	0.2634	0.2663	0	0.2517	0.2881	0.4413
4	0.2446	0.2288	0.2179	0	0.2182	0.2470	0.4501
5	0.4355	0.4226	0.3741	0	0.3678	0.4379	0.5509
6	0.4067	0.3648	0.3725	0	0.3488	0.3582	0.6925
7	0.3371	0.3099	0.3406	0	0.3146	0.3375	0.5248

Numbers of data used to compute coefficients

Ch.	Beam position 1	2	3	4	5	6	7
1	602	621	629	0	630	606	593
2	607	622	628	0	628	609	593
3	609	616	626	0	634	610	538
4	600	616	622	0	628	613	520
5	600	615	623	0	624	613	595
6	604	611	625	0	627	607	568
7	604	612	626	0	625	610	592

Appendix E. Updated limb-adjustment coefficients for SSM/T, satellite F9.

Beam position #1

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	49.52	1.42202	-0.62443	0	0	0	0	0
2	0.30	0.09867	1.01336	-0.10178	0	0	0	0
3	0.46	0	0.12260	1.09872	-0.21494	0	0	0
4	0.72	0	0	0.41779	0.59631	0	-0.01282	0
5	-3.88	0	0	0	0	0.91925	0	0.10100
6	3.19	0	0	0	-0.00305	0	1.34641	-0.35333
7	0.65	0	0	0	0	-0.01398	0.35742	0.65808

Beam position #2

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	12.67	1.11060	-0.15838	0	0	0	0	0
2	-0.42	0.03520	1.01795	-0.04772	0	0	0	0
3	-0.28	0	0.03763	1.07324	-0.10638	0	0	0
4	1.49	0	0	0.18402	0.80713	0	0.00311	0
5	-1.67	0	0	0	0	0.96850	0	0.04003
6	3.49	0	0	0	-0.02185	0	1.12201	-0.11438
7	-0.07	0	0	0	0	0.00372	0.16003	0.83752

Beam position #3

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	1.19	1.02275	-0.02610	0	0	0	0	0
2	-0.42	0.00971	1.00064	-0.00731	0	0	0	0
3	-0.04	0	0.01207	1.01161	-0.02266	0	0	0
4	1.08	0	0	0.05414	0.93604	0	0.00507	0
5	-0.18	0	0	0	0	0.99134	0	0.00977
6	0.70	0	0	0	-0.00012	0	1.03333	-0.03601
7	0.07	0	0	0	0	0.00824	0.05298	0.93860

Beam position #4

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	0.00	1.00000	0	0	0	0	0	0
2	0.00	0	1.00000	0	0	0	0	0
3	0.00	0	0	1.00000	0	0	0	0
4	0.00	0	0	0	1.00000	0	0	0
5	0.00	0	0	0	0	1.00000	0	0
6	0.00	0	0	0	0	0	1.00000	0
7	0.00	0	0	0	0	0	0	1.00000

Beam position #5

Channel

Ch.	Const.	1	2	3	4	5	6	7
1	2.04	1.01405	-0.02132	0	0	0	0	0
2	0.44	0.00673	1.00705	-0.01498	0	0	0	0
3	-0.09	0	0.00827	1.01807	-0.02506	0	0	0
4	0.51	0	0	0.04980	0.94519	0	0.00278	0
5	-0.16	0	0	0	0	0.99213	0	0.00875
6	0.30	0	0	0	-0.00012	0	1.02917	-0.03003
7	-0.21	0	0	0	0	0.00507	0.04321	0.95288

Appendix E (continued).

Beam position #6

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	14.80	1.10047	-0.15804	0	0	0	0	0
2	2.19	0.03121	1.01757	-0.05503	0	0	0	0
3	0.07	0	0.02986	1.08896	-0.11646	0	0	0
4	1.91	0	0	0.18536	0.80273	0	0.00351	0
5	-0.12	0	0	0	0	0.96797	0	0.03289
6	3.21	0	0	0	-0.01294	0	1.13397	-0.13428
7	0.32	0	0	0	0	0.01123	0.17700	0.81079

Beam position #7

		Channel						
Ch.	Const.	1	2	3	4	5	6	7
1	47.30	1.40346	-0.59976	0	0	0	0	0
2	5.21	0.09274	1.00737	-0.11382	0	0	0	0
3	1.40	0	0.09703	1.15347	-0.25087	0	0	0
4	0.63	0	0	0.41510	0.59375	0	-0.01044	0
5	-1.36	0	0	0	0	0.92115	0	0.08369
6	1.59	0	0	0	0.00787	0	1.35669	-0.37024
7	-0.15	0	0	0	0	0.00366	0.38922	0.60876

Standard deviations of fit (degrees K)

	Beam position						
Ch.	1	2	3	4	5	6	7
1	1.4902	1.2178	1.1129	0	1.0878	1.2692	1.3487
2	0.5144	0.4488	0.4410	0	0.4169	0.4755	0.4793
3	0.2402	0.2241	0.2068	0	0.2019	0.2308	0.2414
4	0.2096	0.2094	0.1926	0	0.1951	0.2098	0.1995
5	0.2602	0.2221	0.1973	0	0.2271	0.2208	0.2865
6	0.3045	0.2724	0.2561	0	0.2640	0.2696	0.3242
7	0.2640	0.2498	0.2522	0	0.2476	0.2357	0.2784

Numbers of data used to compute coefficients

	Beam position						
Ch.	1	2	3	4	5	6	7
1	588	616	637	0	631	614	576
2	603	617	637	0	628	611	599
3	608	627	636	0	633	619	608
4	611	623	635	0	635	626	611
5	596	618	625	0	629	611	597
6	607	621	635	0	630	615	603
7	607	619	631	0	627	616	604

(Continued from inside front cover)

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